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THE PERMEABILITY SYSTEM

F. Kapeller
Rock Mechanics Laboratory

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1. INTRODUCTION

The equipment described in this report is used to measure permeability of tight crystalline rock specimens by the transient pulse method developed by Brace et al. (1968). The permeability equipment was manufactured by Pressure Systems Inc., Alamos, California.

This report provides a brief description of the unit functions of the equipment and operating procedures. Modifications to the original equipment have been made and are presented as well.

2. UNIT FUNCTIONS

The permeability equipment consists of four principal components:

1. Sample holder assembly
2. Pore pressure system
3. Confining pressure system
4. Recording units.

2.1 SAMPLE HOLDER ASSEMBLY

The sample holder assembly consists of a pressure vessel and a ported baffle plate which serves as a specimen holder as well as an end plug for the pressure vessel (Fig. 1). Copper jacketed specimens are connected to the specimen holder by means of two pieces of stainless steel capillary tubing which serve as upstream and downstream pore pressure lines during testing.

The sample holder can accommodate four core specimens of about 4.5 cm diam and up to about 8.0 cm in length. Three thermocouple sensors inside the pressure vessel are used to monitor specimen temperature.

2.2 PORE PRESSURE AND CONFINING PRESSURE SYSTEMS

Schematic diagrams of the pore pressure system are shown in Fig. 1 and 2. The pore pressure system consists of two sets of reservoir volumes of 10, 50 and 500 cc capacities. The reservoirs are submerged in a water bath to maintain constant temperatures.

A set of reservoirs are connected to the upstream and downstream ends of a specimen by means of high pressure stainless steel capillary tubing. Pore pressure is applied with an air activated hydraulic pump. Partially de-aired distilled water is used as the pore fluid.

Confining pressure is applied with a hydraulic pump and silicone oil is used as the pressurizing fluid. Thermocouple feed through and the supply port for the confining pressure fluid are fed through the bottom baffle plate of the pressure vessel.

Maximum operating confining pressure is about 70 MPa (10 000 psi).

2.3 RECORDING UNITS

The recording units consist of a multi-channel Honeywell recorder and an Omega recorder. The Honeywell recorder is used to monitor and record pore pressure, pressure pulse, water bath temperature and internal temperature of the pressure vessel as a function of time.

The Omega recorder is used to record pore pressure decay curves.

3. MODIFICATIONS

For purposes of operational convenience and efficiency, it was found necessary to modify the original permeability equipment, as shown in Fig. 1, to the unit schematically indicated in Fig. 2.

The principal modifications which were carried out are the following:

1. complete replacement of electronic system;
2. overhaul of pore pressure and confining pressure systems; and
3. improved sealing arrangement for the pressure vessel.

3.1 MODIFICATIONS TO ELECTRONIC SYSTEM

Redesign and rebuilding of the three(3) electronic systems associated with pressure sensing was carried out due to uncertainties in the calibration of the original equipment. A simplified diagram of one of the systems is shown in Fig. 3. Basically, two DC power supply units provide ±15 volts DC. A special temperature stabilized voltage reference diode LM 299 is used in conjunction with an Op Amp to supress the output voltage of the pressure transducer. This permits the measurement of very small voltage changes which correspond to small pressure changes.

The reference voltage is applied to the "ten turn" potentiometer. The variable output from the potentiometer is applied to amplifier "A" and is connected to the positive side of the transducer which allows zero supression of the transducer output voltage in reference to ground. A voltage divider gives the following measuring ranges.

Ranges (Volts)
0 - 5.00
0 - 2.50
0 - 1.00
0 - 0.500
0 - 0.250
0 - 0.100
0 - 0.050
0 - 0.025

The above divisions apply to both upstream pore pressure (P-up) and downstream pore pressure (P-down) system scales. A similar electronic system but with different scale divisions is used for monitoring the differential transducer (Δ-scale) output. With the later system the differential transducer sensitivities are increased by a factor of ten and the ranges are as shown below:

Range (Volts)	
0 - 0.500 = (500 psi)	3.45 MPa
0 - 0.250 = (250 psi)	1.73 MPa
0 - 0.100 = (100 psi)	0.69 MPa
0 - 0.050 = (50 psi)	0.345 MPa
0 - 0.025 = (25 psi)	0.173 MPa

With each pressure system a voltage follower "Op Amp B" is used to reduce loading effects on the range switch; the outputs are fed into Honeywell and Omega recorders to provide permanent records of pressure for analysis.

A digital voltmeter is used to measure individual thermocouple voltages. A multiwafer switch is used to connect individual thermocouples to the voltmeter at the input to the Honeywell recorder. One hundred divisions on

tne Honeywell recorder corresponds to 25MV. Type E thermocouples are used with a zero degree (°C) reference point supplied by 3-omega battery operated electronic ice points. The water bath temperature can also be monitored with the voltmeter using the same switch.

In this case, the temperature is indicated directly in °C using the 100-microvolt range on the digital voltmeter. A permenent record of water bath temperature, can be obtained on tne Honeywell recorder; 100 divisions correspond to 50°C. The water bath temperature is maintained at aoout 25°C.

3.2 MODIFICATIONS TO RECORDING UNITS

Two recorders are being used to ooserve several functions of tne system in different time modes. A Honeywell eight-channel recorder with a chart speed of about 2.5 cm (1 in.) per hour is used to observe tne following seven test functions: tnree thermocouple sensor outputs in the confining pressure vessel; upstream (P-up); downstream (P-down) and differential (W) pore pressures and water bath temperature.

An Omega recorder with variable recording speeds (25, 20, 12.5, 10, 5 and 2.5 cm/n) is used to monitor upstream and downstream pore pressure decays during testing. A three position toggle switcn permits increasing tne individual speeds to a total of 17. Speed selection is dependent on specimen length, rock type and reservoir volume selected.

3.3 MODIFICATIONS: HEATER CONTROL

A cylindrical muffle furnace is used to heat tne test chamber and specimens from room temperature to experimental temperature for neating. The two elements of the neater which were originally wired in parallel, were rewired in series to reduce heat output (Fig. 4).

3.4 MODIFICATION TO PRESSURE VESSEL SEALING ARRANGEMENT

The sealing arrangement originally devised for the confining pressure vessel consisted of a square shaped aluminum ring deformed with a tapered end plug. A 30-ton jack with a special adapter was required to deform tne aluminum ring sufficiently to provide a good seal and blows from a 10 lb hammer was required to secure the end plug nut.

A simpler system has been devised which makes use of a standard O-ring to provide a seal. The O-ring is inserted between the specimen holder

(end plug) taper and the aluminum ring as shown in Fig. 5. The modified system can be hand sealed without the use of any hydraulic equipment. For high temperature applications, Viton or Teflon O-rings are used. The modified sealing arrangement also provides an easier means of disassembling the equipment after use.

4. OPERATING PROCEDURES

4.1 SPECIMEN PREPARATION AND JACKETING

Rock core specimens used in the measurements are limited to 4.5 cm dia due to constraints imposed by specimen end plattens and the diameter of the copper sleeve. Steps in specimen preparation and jacketing are as follows:

a) Specimen ends should be lapped parallel to ±0.03 mm and made square to the longitudinal axis.

b) Measure and record specimen length and diameter to the nearest ±0.01 mm.

c) Cut a copper sleeve about 40 mm longer than specimen length.

d) Jacket rock specimen with a small hand press and ensure that copper jacket extends about 20 mm on both ends of the specimen. Slip two metal rings over the jacketed specimen.

e) Slightly flare both ends of the copper jacket to accommodate the tapered end plattens. Press one platten (with the smaller end facing specimen) until it is in contact with specimen. Repeat the procedure with the second platten.

f) Mechanically seal the jacketed specimen assembly by pressing the metal rings toward the large end of the nearest platten. About 1.4 KN (3000 lbs) force is required to obtain an effective seal.

Care must be exercised in sealing specimen in order to prevent intrusion of the pressurizing fluid.

4.2 INSTALLATION OF SPECIMEN

a) Attach jacketed specimen to the specimen holder with 4.8 mm (3/16 in.) OD stainless steel tubing.

b) Attach two pieces of tubing to the top of the specimen holder.

c) Connect tubing to the "T" junction on manifold located at about 30 cm above the pressure vessel end plug (Fig. 6).

4.2.2 CHECK FOR LEAKAGE

a) Connect the specimen assembly to vacuum system by opening valves 24 and 25 (Fig. 2).

b) Evacuate specimen assembly for at least 24 h; close valve 25 and observe and record height of mercury column.

c) Record barometric reading. Allow vacuum system to equilibrate for about 30 minutes, then observe and recored new mercury level.

d) Observe vacuum system over six hour period, if no large changes in the mercury level are observed, over a period of six hours, the specimen jacket assembly can be considered sealed.

(Note: fluctuations in barometric pressure can cause slight changes in the mercury level).

4.3 AIR PERMEABILITY MEASUREMENTS (OPTIONAL)

The following procedure may be followed in carrying out air permeability measurements.

a) Disconnect one side of the pore pressure line at the "T" block and plug the port as shown in Fig. 6.

b) Attach a valve to the free end of the tubing with the other side of the valve opened to the atmosphere.

c) Turn on vacuum pump and open valves 24 and 25; close the newly attached valve and establish full vacuum.

d) Close valve 25, note and record height of mercury column, and time.

e) Allow mercury column to drop down to a predetermined height (about 5 cm, below the initial mercury column reading) and note time.

f) Repeat steps c to e.

g) Determine average flow rate "q" from the dimensions of the capillary tubing, the diameter of the manometer tube and pressure decay data.

h) For approximate permeability to air calculations, see Ref. (1).

The air permeability of a rock specimen can be measured under confined pressure conditions with the system. For this purpose insert the specimen assembly in the pressure vessel and apply the desired confining pressure. Repeat steps (b) to (h) as described above. (Also refer to section dealing with "Application of confining pressure.)

4.4 PERMEABILITY TO WATER MEASUREMENTS

To carry out permeability to water measurements:

a) Insert the specimen assembly in the pressure vessel and seal the vessel.

b) Apply confining pressure as described earlier. Before confining pressure is applied, however, leave ends of the capillary tubing open and put a clean paper/cloth underneath the open ends of the tubing.

c) Check for oil at the ends of the capillary tubing to assure that there is no leakage in the jacketed specimen assembly. Should this occur, stop the test and start with a new specimen.

d) If no leakage is detected over a twelve hour period, connect the capillary tubings to the individual sets of manifold valves making certain they are correctly connected to the upstream and downstream ends of the specimen (Fig. 2).

e) Close all valves on the manifold. Release the confining pressure by opening valve 6. Switch on the vacuum pump and evacuate specimen, i.e., open valves 23, 24 and 25 (Fig. 2).

f) Observe and record the height of mercury column and the pressure gauge reading. (Note: Low vacuum pressure may be due to leakage in the filter, Fig. 2.)

g) Close valves 15U to 22D. Open valves 15 SU and 16 SD (Fig. 2). Evacuate specimen for about two hours then close valve 25 and observe mercury column. The mercury column height should range between 74 and 76 cm, depending on atmosphere pressure conditions. Excessive or rapid drop in the mercury level could signify leakage between valve 25 and the specimen holder assembly.

4.4.1 Application of Soaking Pressure

a) Reapply confining pressure to the specimen.

b) With valves 1, 3, 4, 7, 8, 11 and 12 closed, open valve 2 and vent gas in water gas separator.

c) Open valves 2, 3 and 7, and then air valve 10. This process starts the pump and pushes the piston in the separator to the gas side. Gauge I reading should not exceed 20 MPa (3000 psi) for normal operation.

d) When pumping stops, close air valve 10 and valve 2 and then open valve 4 and maintain it in an open position until no pressure is visible on gauge I, (Fig. 2). Close valves 4 and 7.

e) Open gas bottle (Helium or Argon gas) and set regulator at a level where the needle on the low pressure gauge just starts to rise.

f) Close valve 23 and then open valves 1 and 12 and observe gauge III. Open valves 15 SU and 15 SD or any other set of valves where a specimen is connected.

g) Increase gas pressure gradually until desired soaking pressure is reached (on gauge III). Do not exceed maximum capacity of gauge III.
Note: Soaking pressure may have to be adjusted several times during the soaking process and must be closely monitored as it is easy to damage gauge III. Soaking may take up to four days depending on rock type and specimen size.

h) After the soaking cycle is completed, gently close the upstream and downstream valves as well as valve 12 so that no pressure surges are generated in the system.

4.2.2 Application of Pore Pressure

a) Adjust confining pressure to desired test pressure.

b) Close valves 13 and 14 and adjust volumetric reservoir to desired test pressure. (For example for a 3.5 MPa (500 psi) test pore pressure, the spindle should be unscrewed to about the 3/4 mark Fig. 2).

c) Close valve 11, then open valve 10. At this stage the pump will start to operate and will eventually stop after a few strokes. The pressure reading on gauge I should not exceed 20 MPa (3000 psi). Close valve 10 and and very gently open valve 11. (Be prepared to close valve 11 suddenly in case pressure rises too quickly on gauge IV).

d) With valves 10 and 11 closed, open valves G, A, B, C, D, E, F, 13 and 14. Adjust volumetric screw until desired pressure is attained. Monitor pressure on gauge IV, Fig. 2.

4.4.3 Switch Positions and Their Functions

a) The ten positions of the position selector switch permits connection to the following for monitoring purposes:

Position 0 = Digital voltmeter or external input.
1 = ΔP up 25 mV max voltage to recorder.
2 = ΔP down 25 mV max voltage to recorder.

3 = ΔP differential 25 mV max to recorder.

4 = Type E thermocouple.

5 = Type E thermocouple.

6 = Type E thermocouple.

7 = Water bath temperature direct in °C.

8 = P up direct max 5 V = (7500 psi) 51.7 MPa.

9 = P down direct max 5 V = (7500 psi) 51.7 MPa.

10 = Differential direct max 0.5 volt (500 psi) 3.5 MPa.

Listed below are the voltage atinuation switch ranges for the upstream (P-up) and downstream (P-down) pore pressure transducer output to the Honeywell recorder.

Input Ranges		Output to recorder
5.17 MPa (7500 psi)	= 5 volt	25 mV
	2.500	25
	1.000	25
3.45 MPa (500 psi)	0.500	25
	0.250	25
	0.100	25
	0.050	25
	0.025	25
	0.00 Position input to recorder is shorted.	

On the Delta transducer (ΔP differential) range switch, the following three positions - 1.0, 2.5, and 5 volts are eliminated. Refer to Fig. 7.

b) To carry out permeability measurements select appropriate reservoirs or any suitable combination there of. (For example, 10 cc reservoirs may be be used for tight rock formations.)

c) With upstream and downstream soaking pressure valves closed (e.g., 15 SU and 16 SD) open the corresponding upstream and downstream pore pressure valves (e.g., 15 U and 16 D).

d) If soaking pressure applied to a specimen is considerably lower than the operating pore pressure, a pressure drop of up to 40% can be expected during the pore pressure stabilization process. Should this occur, open valves 13, 14 and G and re-adjust pressure with the volumetric screw. Close valves after the adjustment.

4.4.4 Recording and Sensitivity Adjustments

The position selector switch on the front panel is used to visually monitor the equipment parameters indicated in section 4.4.3.

a) To monitor the upstream pore pressure with the digital voltmeter display, the position selector switch is set to 8, the function selector switch to DC and the range switch to 1 volt. The upstream pore pressure on the digital voltmeter display is indicated in volts. For example, for an upstream pore pressure of 3.5 MPa (500 psi), the corresponding reading on the voltmeter display panel will be 0.333 volts. (Note: 1 mv = 10.34 kPa (1.5 psi).

b) To monitor the downstream pore pressure the position selector switch is set to 9.

c) To monitor the equivalent analogs of pore pressure at the recorders:

(i) Set the position selector switch to 1, 2 or 3 to monitor ΔP up, Δp down or ΔP differential, respectively.

(ii) Set the range switch to the 0.100 volt position.

(iii) Rotate the offset potentiometer until the voltmeter reads +0.020.

(iv) Set the voltmeter range switch to 100 mv, the display should read 20 mV.

(v) Turn on the Honeywell recorder; the numbers 1, 2 or 3 will be printed out at about 0.8 margin of the chart. (Note: the Honeywell and Omega recorders have total deflections of 25 mV.)

Note: Pressure drops of several millivolts can be expected during the initial stages of the pore pressure stabilization process. This may occur over a period of up to two days. Should this occur, reset the offset potentiometers to stay on range.

4.4.5 Testing Procedure

a) After the pore pressure has stabilized (indicated by zero pressure gradient), close the differential pressure valve "G" Fig. 2. A small rise in pressure can be expected after valve closure especially when small reservoir volumes are used. However, this can be offset by adjusting the upstream and downstream pore pressure valves on the manifold (e.g., 15 U and 15 D Fig. 2).

b) To record measurements on the recorders, zero the downstream voltmeter reading with the potentiometer offset. (Note: Actual pore pressure reading will be as indicated on the digital voltmeter display in volts, for example, a stabilized pore pressure reading of 3.5 MPa will be indicated as 0.333 volts).

c) Record pressure on gauge IV and compare to equivalent pressure reading on the digital voltmeter. Note any discrepancies between the two readings.

d) Close upstream pore pressure valve on the manifold and valve 13, (for example valve 15 U, etc.), then open valve 13 and increase the upstream volumetric pressure by the desired pressure pulse (a maximum of 25 mV or equivalent pressure may be applied. Assuming an equilibrium pore pressure of 3.5 MPa, or 0.333 volt equivalent, the new voltage reading will be about 0.358 volts or 3.71 MPa (537.5 psi).

e) Fine adjustment to the pore pressures can be made with valves A, B or C, depending on the selected reservoir volumes being used for a measurement.

f) Allow the system to stabilize for at least ten minutes and monitor outputs on channels 1 and 2 on the Honeywell recorder. Upstream and downstream pressures are printed as "1" and "2", respectively.

Note: The Honeywell recorder is recommended for recording the pore pressure decay for low permeability rock specimens because of its slow chart speed (about 2.5 cm per hour). For high permeability rocks, the Omega recorder with variable chart speed is recommended.

4.4.5.1 Procedures for using Omega recorder

a) Switch recorder on and select chart speed.

b) Set range switch at 100 mV.

c) Considering the equilibrium pore pressure as the base pressure on the recorder, zero recorder pens at the right hand margin of recorder chart paper using the correct offset potentiometer. (Note, this is reserved on the Honeywell recorder.)

d) A 25 mV or 0.26 MPa (37.5 psi) maximum pressure pulse superimposed on the upstream pressure should move the upstream recorder pen to the extreme left hand margin of the Omega recorder chart paper.

e) Select a suitable chart speed and monitor the upstream and downstream pressure traces on the recorder chart paper for about 10 minutes. Normal traces should be horizontal straight lines.

f) Record upstream and downstream equilibrium pore pressures, reservoir volumes being used, pressure pulse, chart speed relevant specimen data and the starting time of an experiment on the chart paper.

g) Open the upstream pressure valve on the manifold slightly (e.g., valve 15 U, Fig. 2). A typical set of pore pressure decay curves similar to a capacitor discharge curves is shown in Fig. 8.

h) The test may be considered to be completed after about 90% of the pressure pulse has decayed.

i) For further analysis of the decay curves, refer to Ref. 1.

4.5 OPERATION OF CONFINING PRESSURE SYSTEM

Refer to the following switches and valves on the front panel of the permeability equipment, Fig. 9. Valves 5, 6, 9 and a Ball valve. To operate the confining pressure system:

a) (i) Close valves 5 and 9;

(ii) Open valve 6;

(iii) Put ball valve in the "up" position.

b) Switch on the electric pump. With the top baffle plate of the pressure vessel removed, a small jet of oil can be seen on the bottom of the vessel as the oil starts to fill the chamber. Replace and secure sample holder assembly with nut (Fig. 5).

c) Monitor the oil level in the vessel by removing one of the spare pore pressure port plugs; this enables any entrapped air to escape.

d) As soon as oil appears at the plug, close valve 6, switch off the electric pump and insert plug in the specimen holder port.

e) Apply desired confining pressure by opening valve 5 and operating hydraulic pressure hand-pump until desired pressure is achieved.

Note: A low oil level in the hydraulic pump reservoir may result in sluggish operation of hand-pump. Should this occur, open valve 9 and switch on the electric pump. Let pump run for a few minutes in order to fill oil reservoir. Switch off pump, close valve 9 and again use the hydraulic hand-pump.

f) To drain the confining pressure vessel:
   (i) Open valve 6;
   (ii) Set the 4-way valve in a down position;
   (iii) Switch on electric pump.
   (To speed up pumping action, open one of the spare plugs in the specimen holder assembly [Fig. 5].)

g) For elevated temperature tests, initially apply a confining pressure less than the desired test pressure. Keep close watch on the confining pressure gauge because of the pressure rise caused by expansion of the silicone oil with temperature. Should confining pressure exceed the desired test pressure, open valve 6 slowly and reduce the pressure to the desired level.

h) Repeat step "g" above until the desired test temperature is reached and pore pressure equilibrium is maintained.

i) Increase confining pressure to the desired test pressure and carry out permeability measurements.

ACKNOWLEDGEMENTS

I wish to thank Mr. G. Larocque and Mr. A. Annor for their assistance in writing this report; Mr. D. Dugmore for preparing the figures; and all others who supported me.

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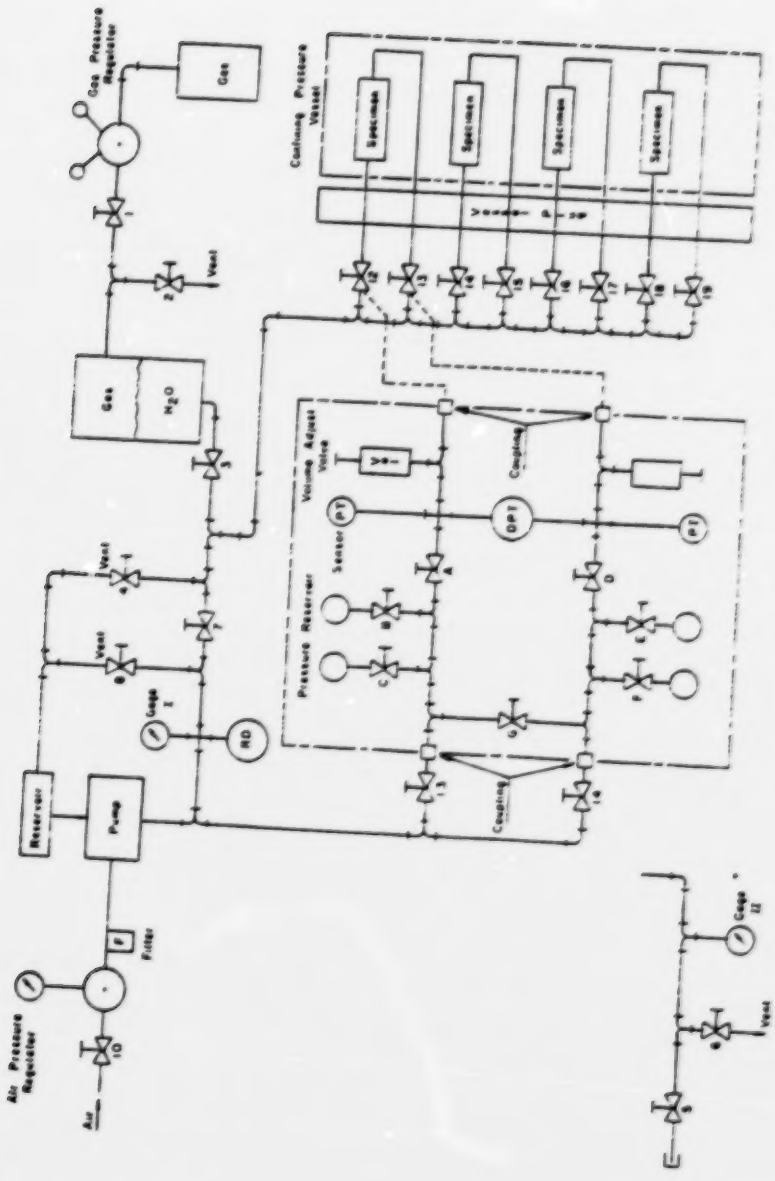


Fig. 1 - Schematic of the original permeability equipment

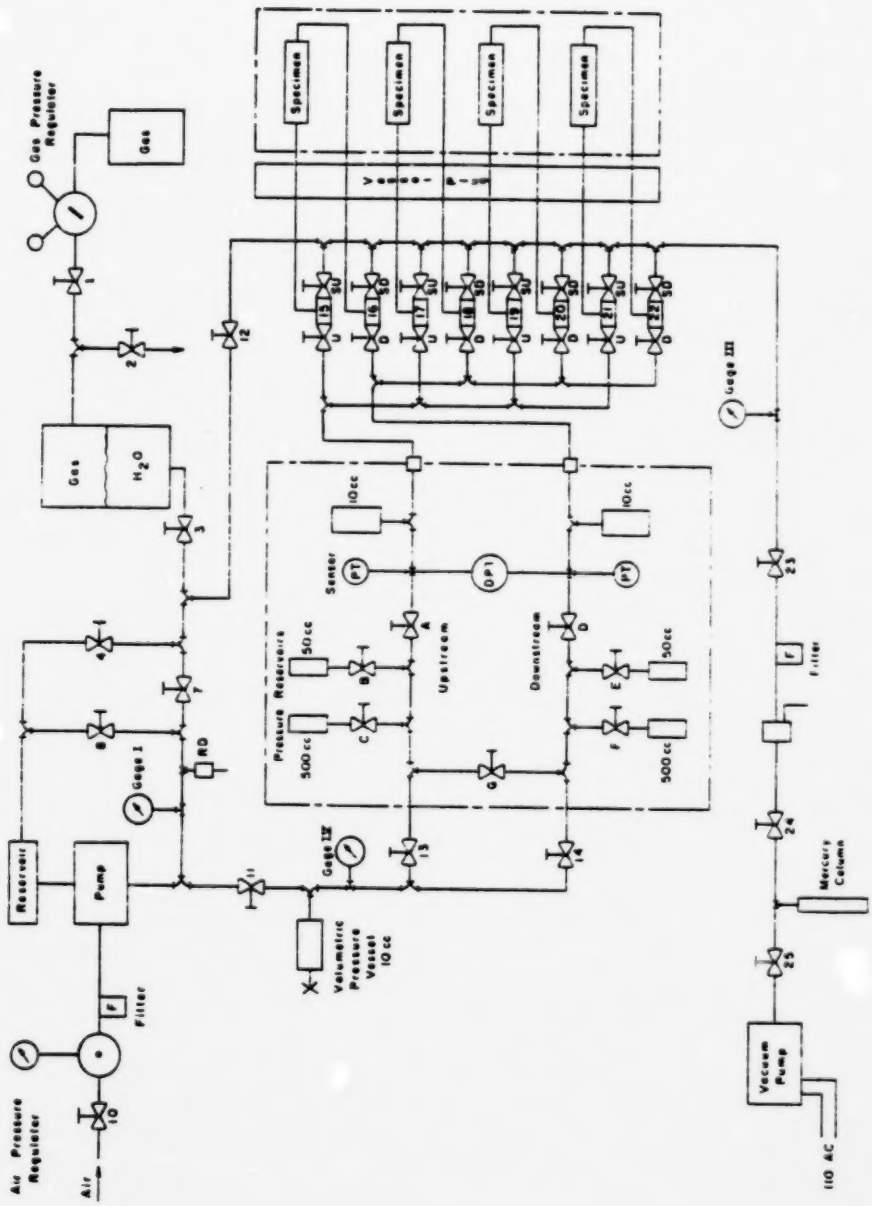


Fig. 2 - Schematic of the modified permeability equipment

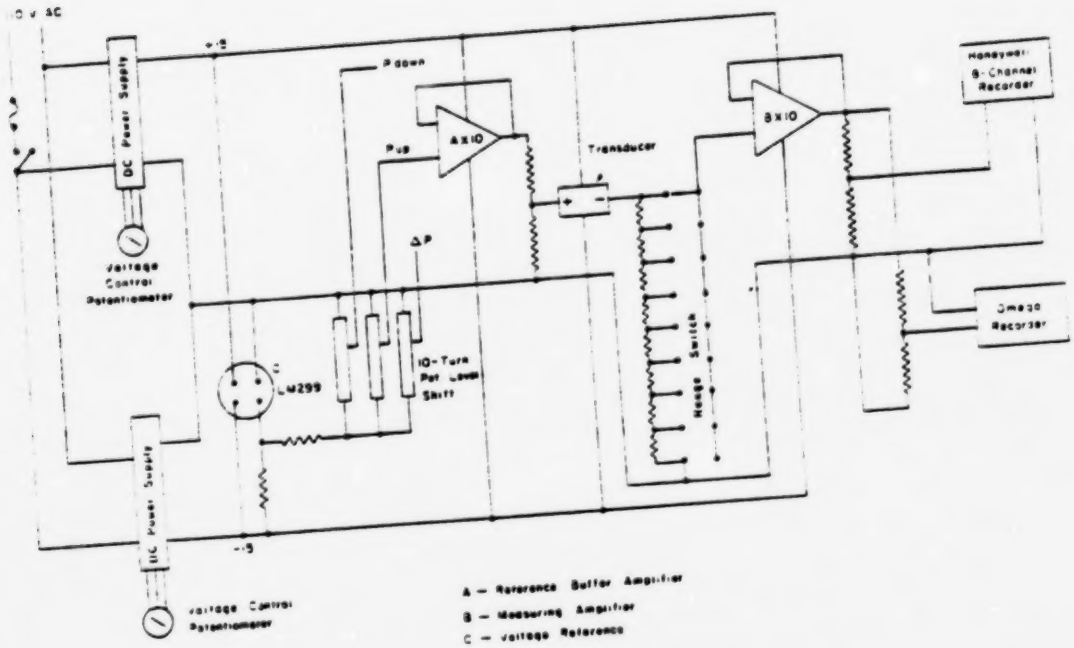


Fig. 3 - Electronic diagram

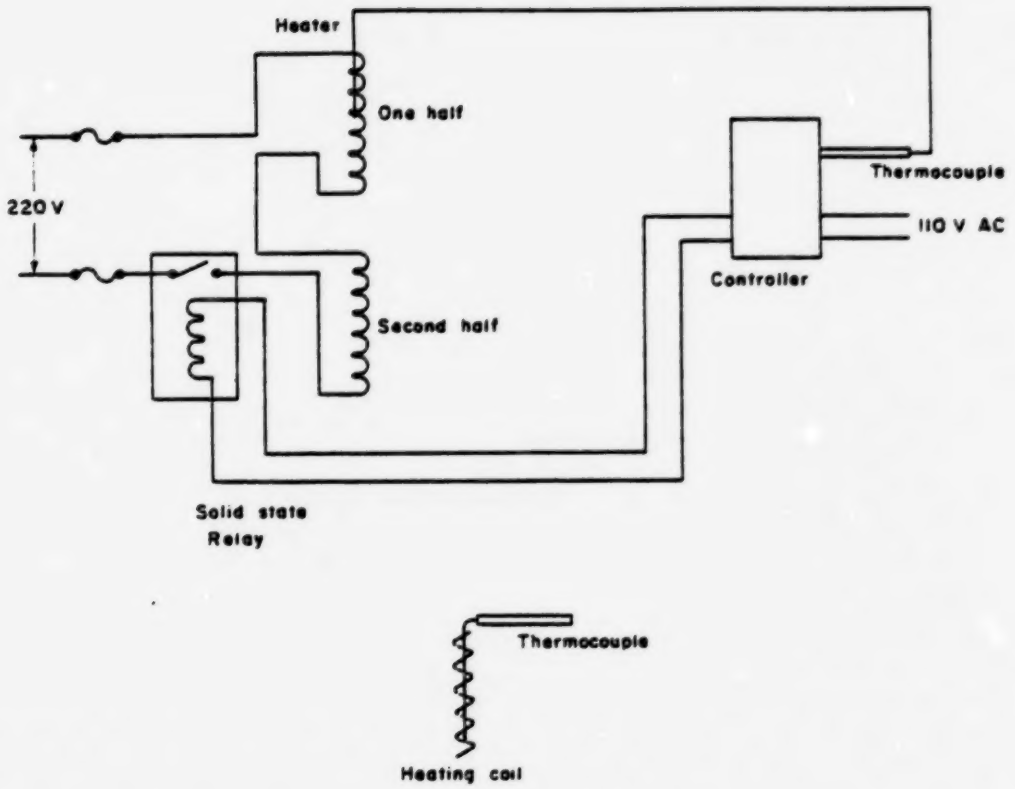


Fig 4 - Schematic of modified muffle furnace

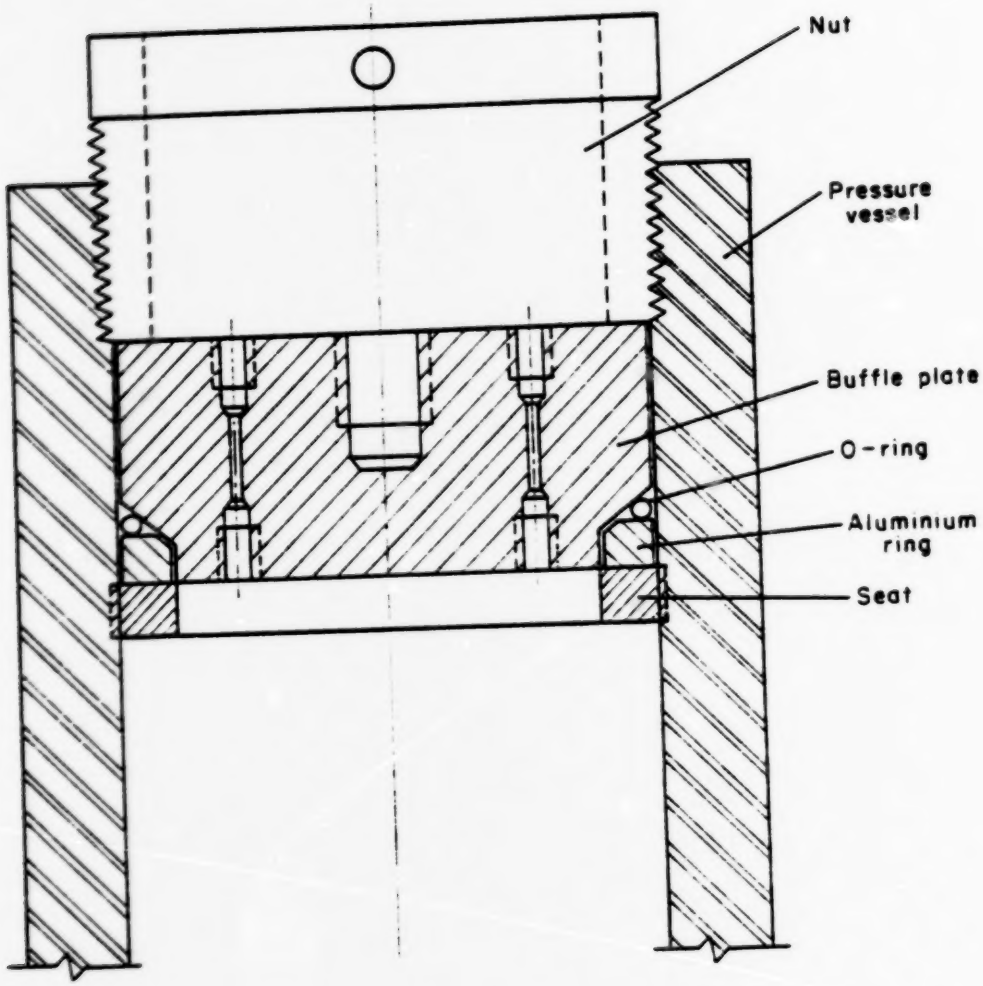
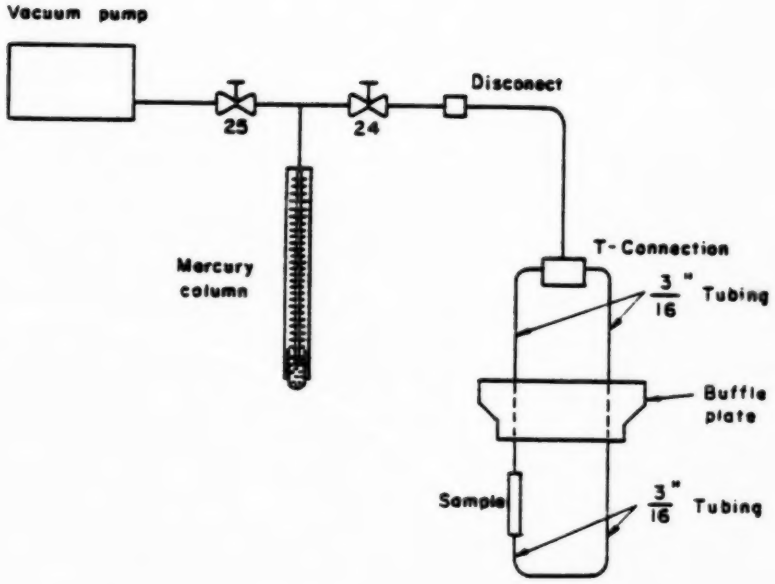


Fig. 5 - Diagram of modified pressure vessel sealing assembly



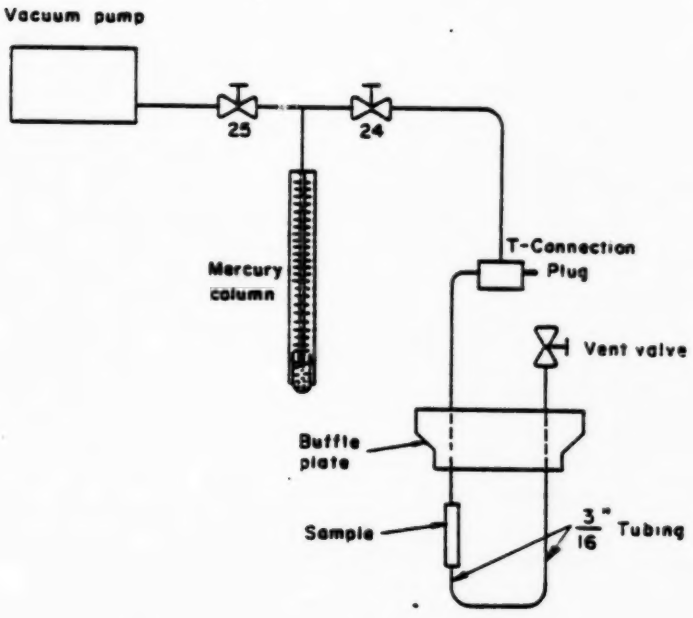


Fig. 6 - Vacuum pressure system and air permeability apparatus

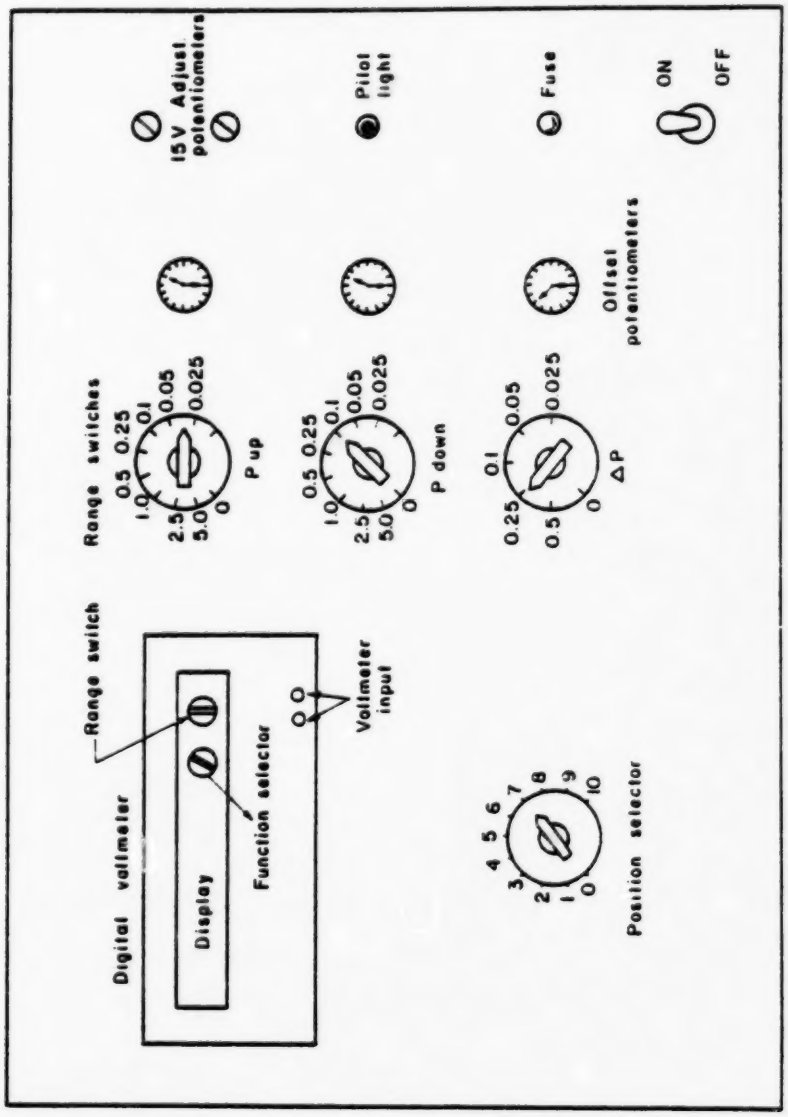


Fig. 7 – Switch positions and their functions

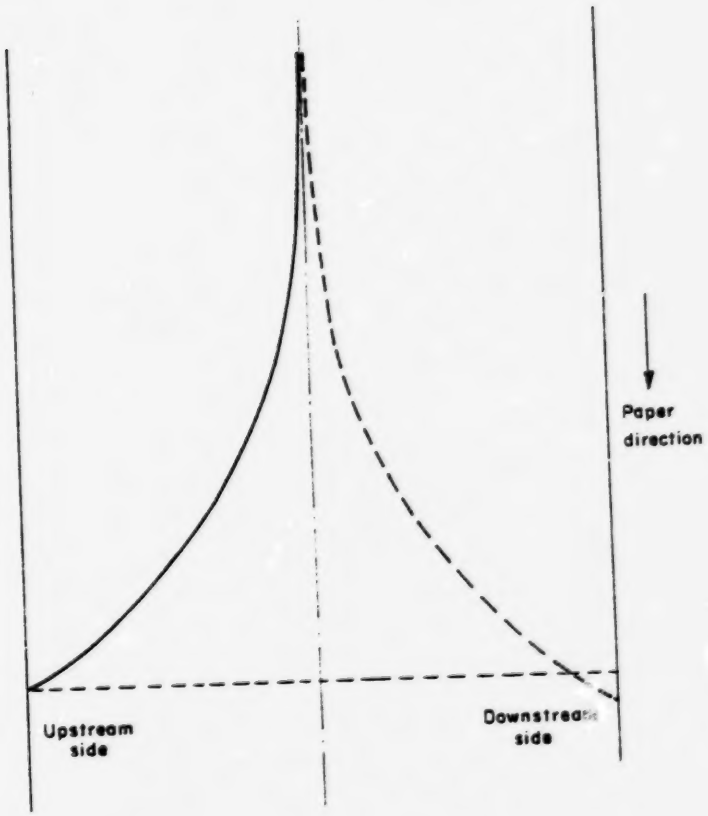


Fig. 8 - Pressure decay curves

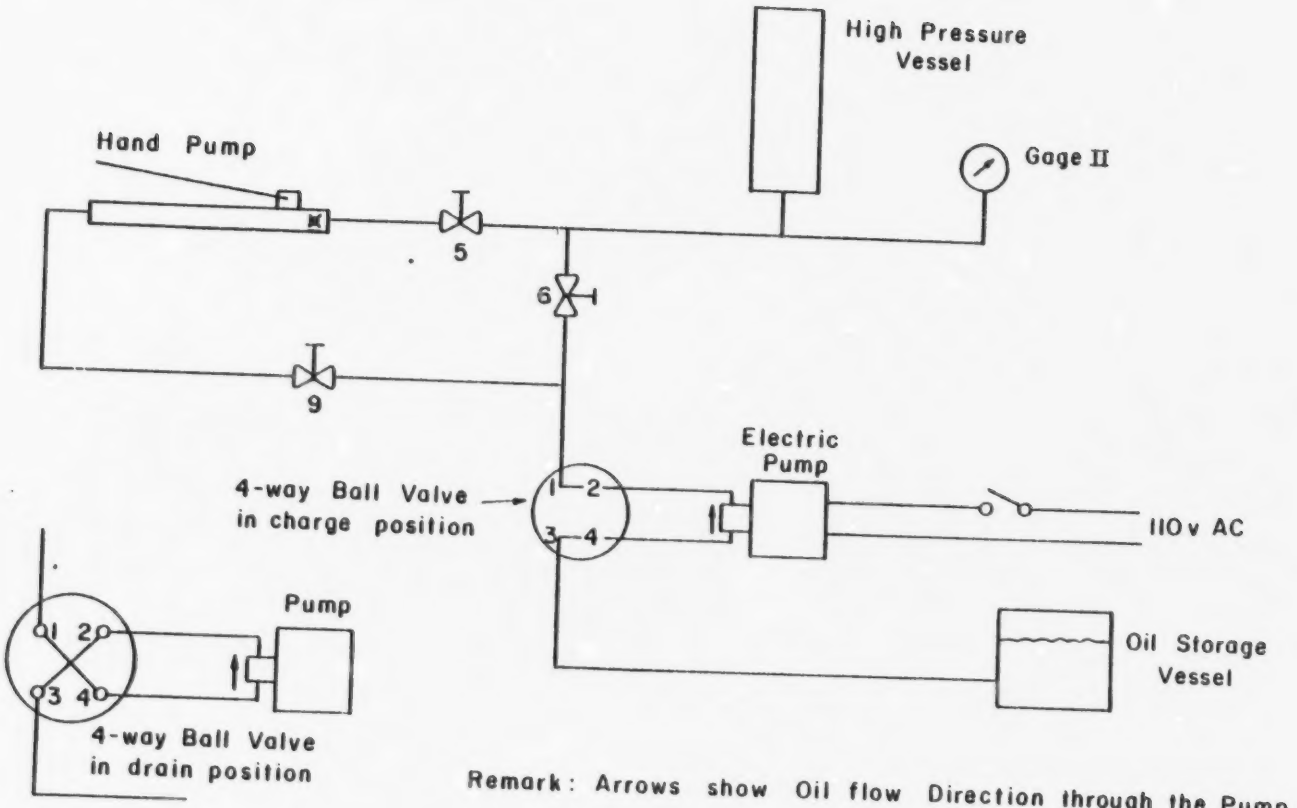


Fig. 9 - Schematic of modified confining pressure system

POOR

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